Modeling GPS Positioning Errors due to Ionospheric Scintillation

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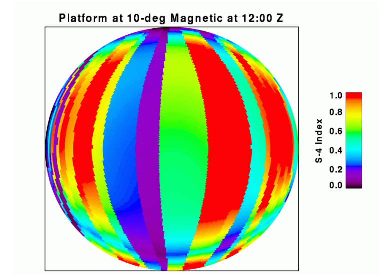
Outline

- Program components
  - Bench-top simulation with SN (WPAFB)
  - Waveform simulation (data, models)
  - Modeling GPS receiver errors
  - Modeling GPS system impacts (SN)
- Characterize scintillation-induced GPS positioning errors from actual data
- Principal scintillation effects on GPS navigation
- Ad hoc model description and preliminary results

GPS Modeling & Simulation Capabilities: The Right Tools for the Job

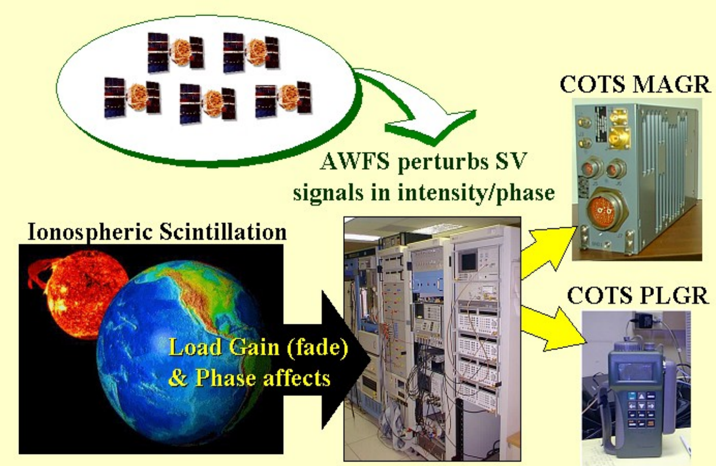
Neither cost-effective nor feasible to perform comprehensive field tests on all GPS UE

- Essential components for high fidelity GPS simulations exist
  - Complex scintillation waveforms (VS Hanscom)
  - "Hardware-in-the-loop" wavefront simulation capability (SN Wright-Patterson)
  - Battlespace scintillation scenario generation and simulation (VS Hanscom; SN Wright-Patterson;
- Upgrades to waveform generation and wavefront simulation technologies required
  - Improvements in resolution, phase control, etc. required for SNRW capability
  - VSBX enhancements to waveform generation
- Goal to produce dual-frequency GPS nav error products tailored to operational UE achievable



IONSCINT-G

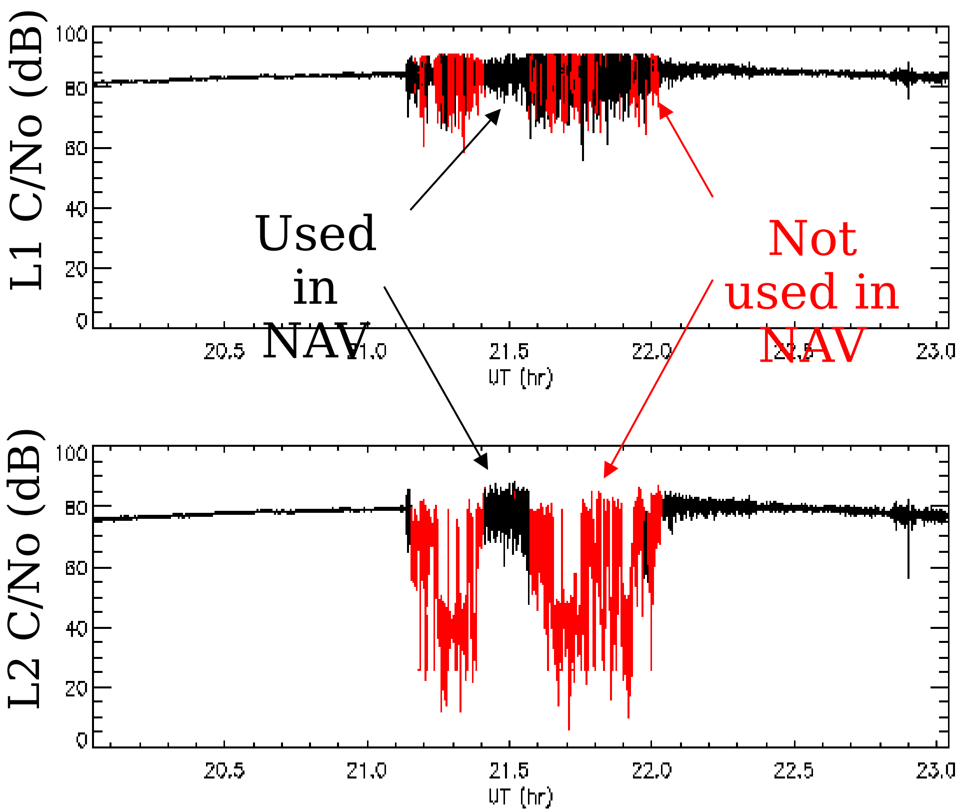
SNRW Hardware Simulat



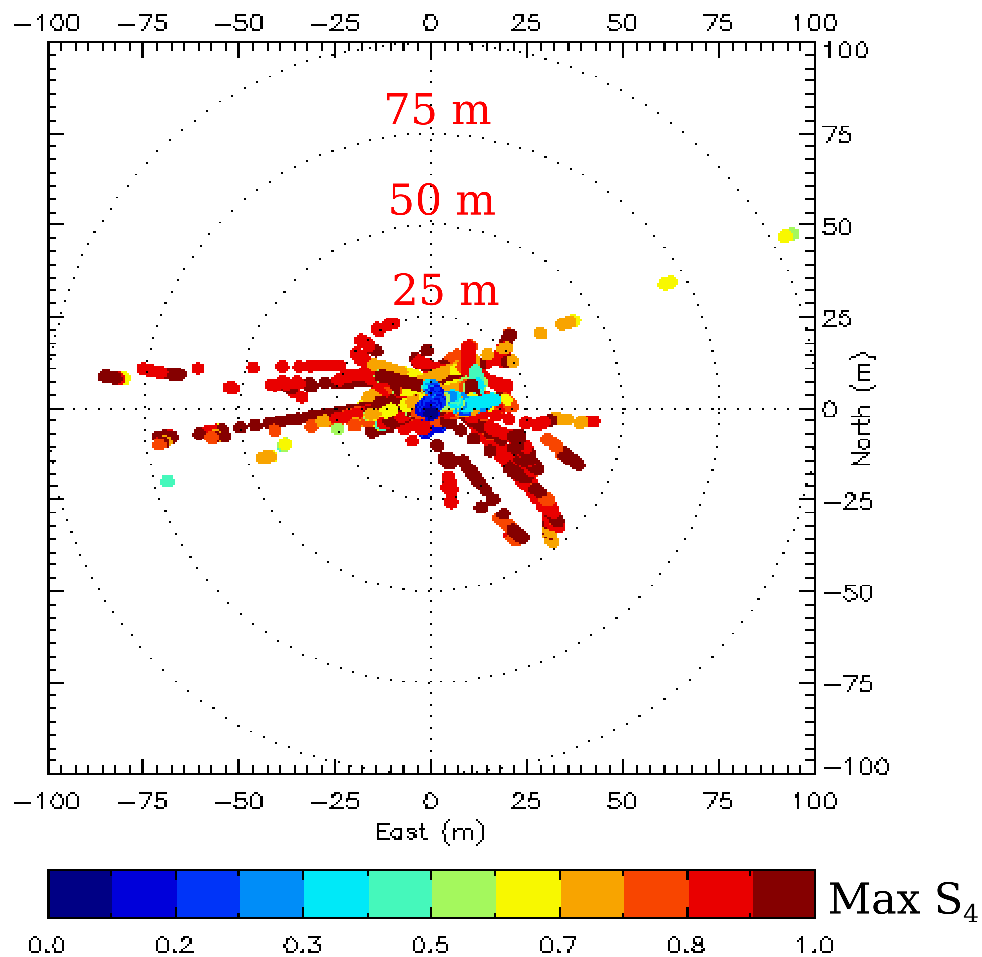
Investment in existing M&S technology needed

Scintillation Effects on Positioning Accuracy

16 Mar 2002, ASI



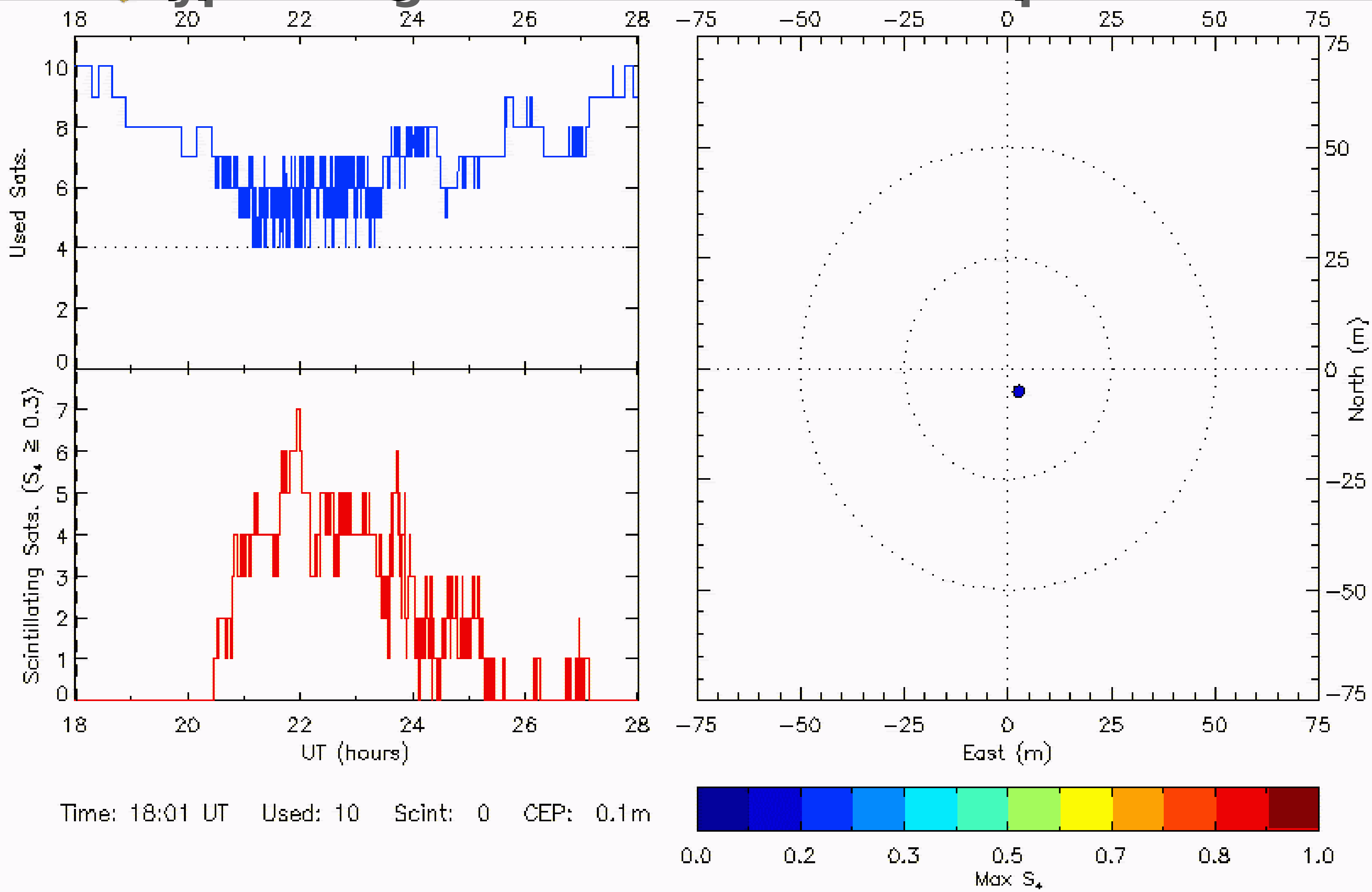
Scintillation Causes Fading of L1 and L2 GPS Signals



Resulting Positioning Error

GPS Positioning Errors During Solar Max

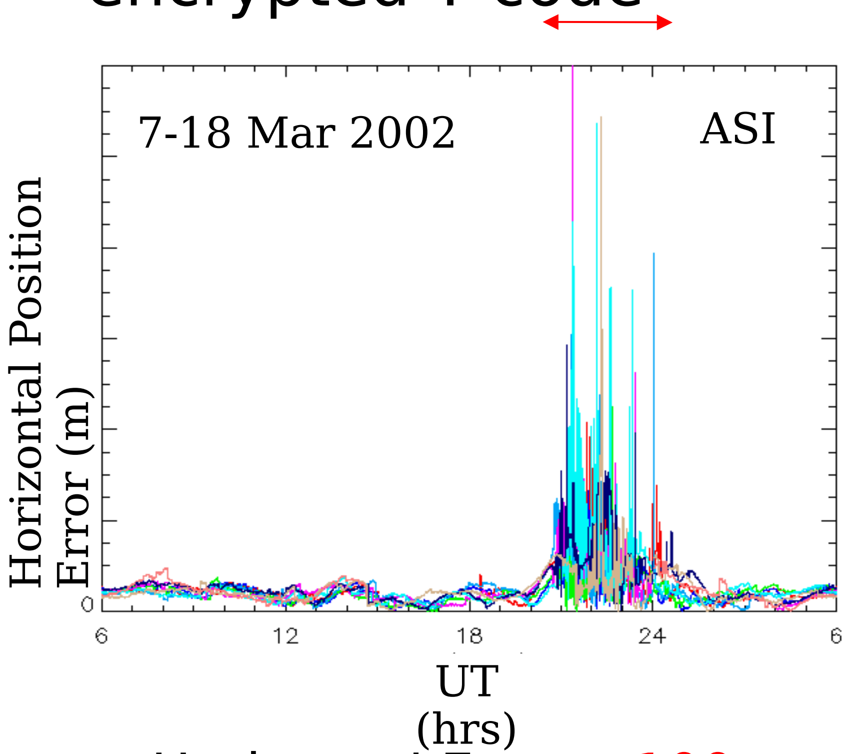
Scintillation can cause rapid fluctuations in GPS position fix;
Typical night from recent field experiments



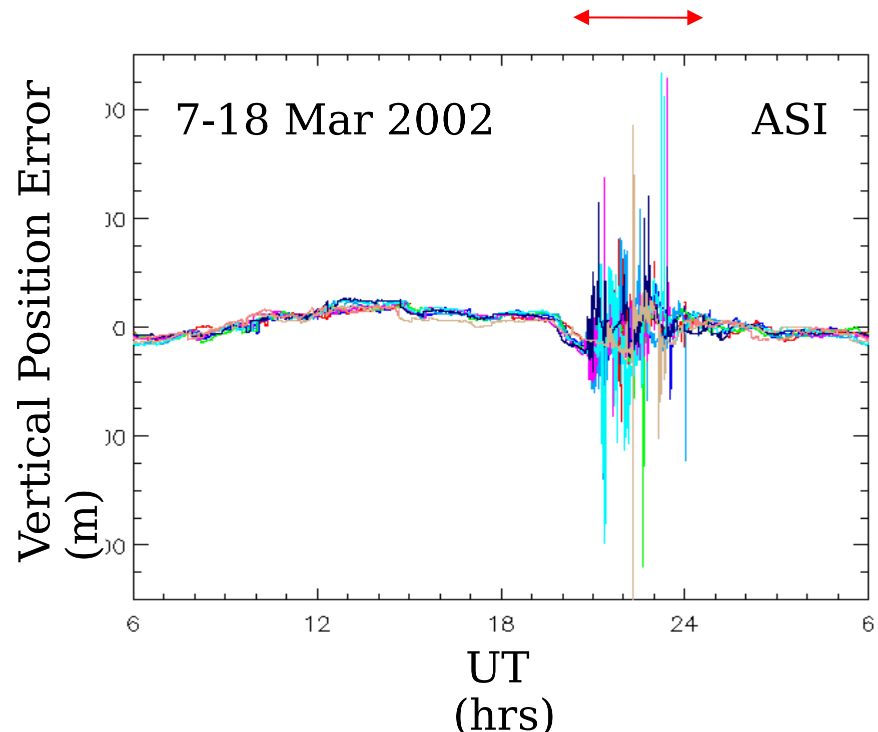
Representative Positioning Errors Near Solar Maximum

Position from dual frequency receiver with access to encrypted Y code

Active Ionosphere 21:00-23:30 UT



Horizontal Error >100 m

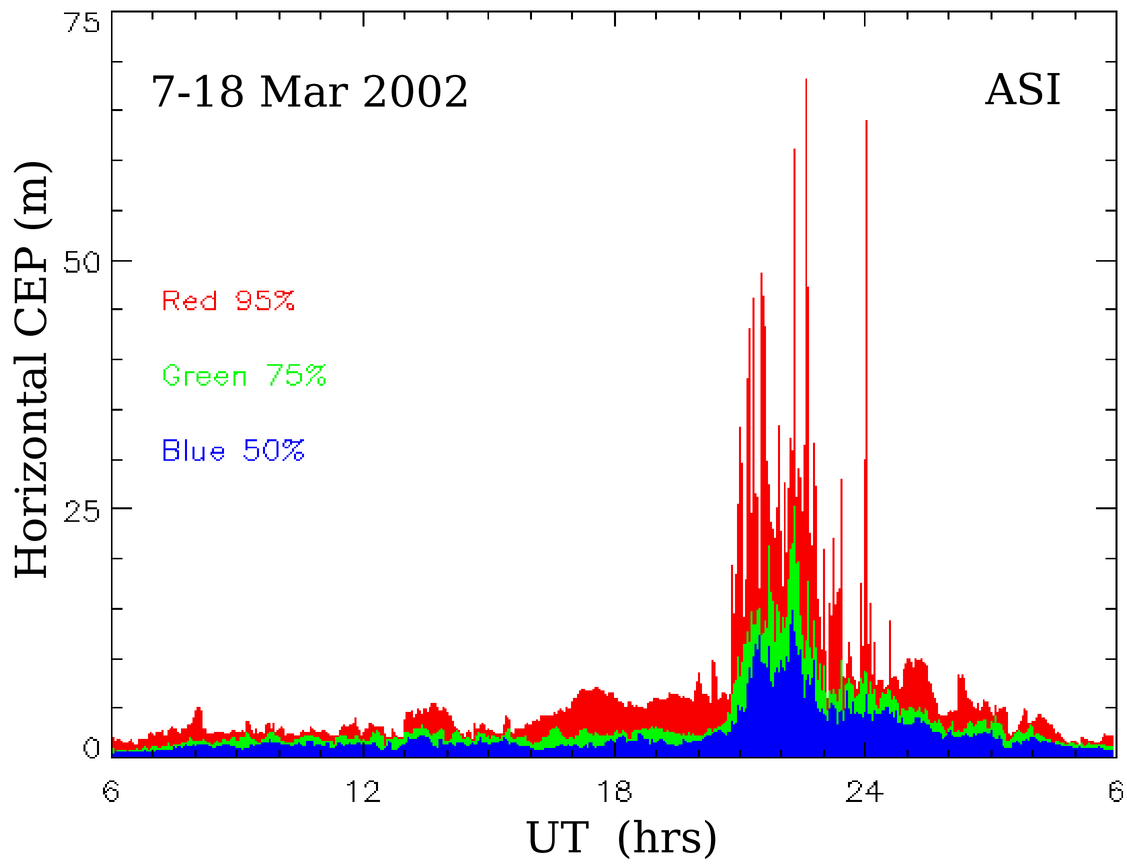


Vertical Error > +/- 200 m

Statistical Analysis of Positioning Errors

Circular Error Probability: probability that error will exceed a given level

A possible metric for a position error product



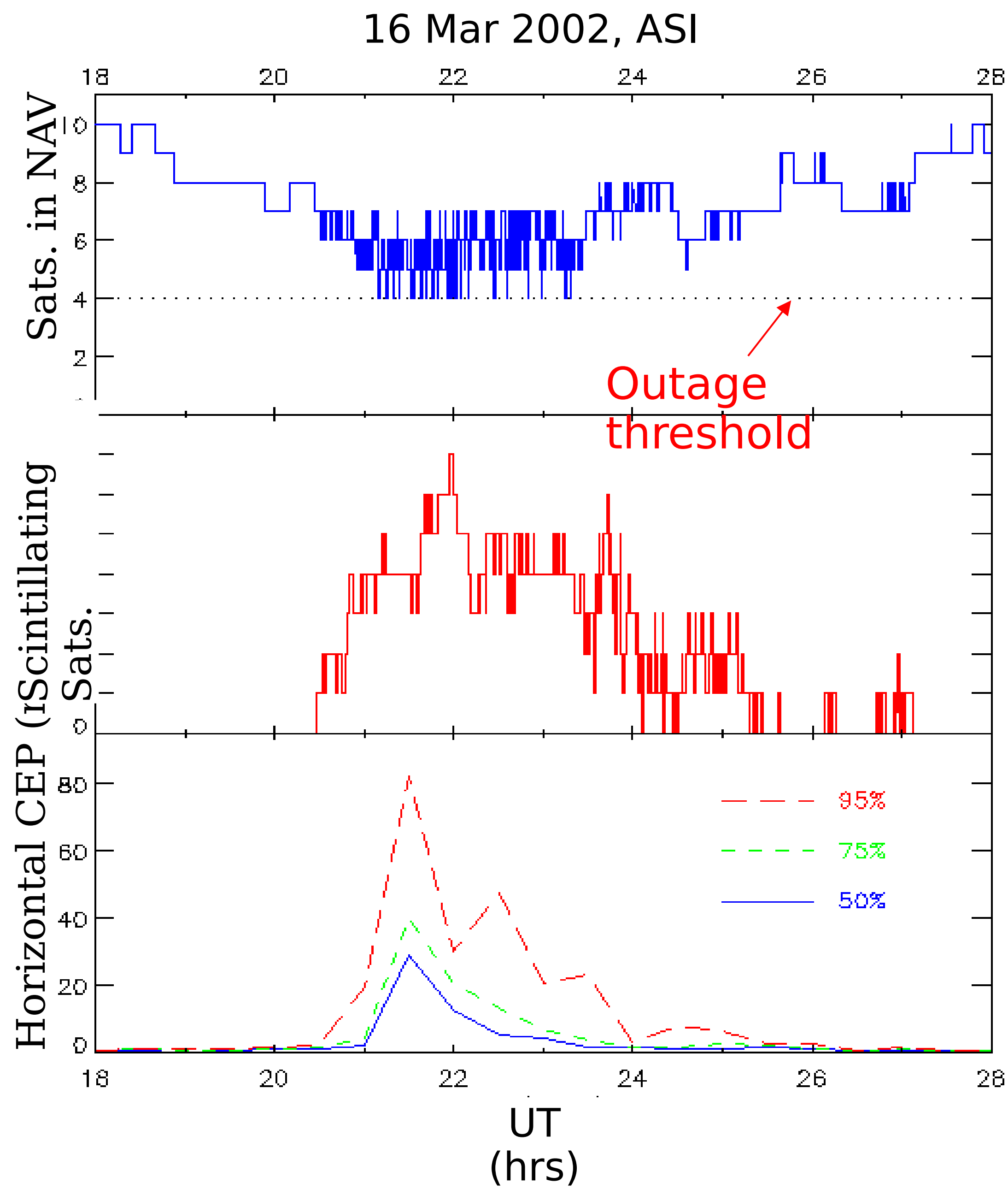
Single point positioning error (2D) better than 10 meters 95% of the time ... except during scintillation

Scintillation Degrades Effective Geometry of the GPS Satellite Constellation

Scintillation causes "Intermittent availability"

All visible satellites were scintillating at 22 UT
(not uncommon at ASI)

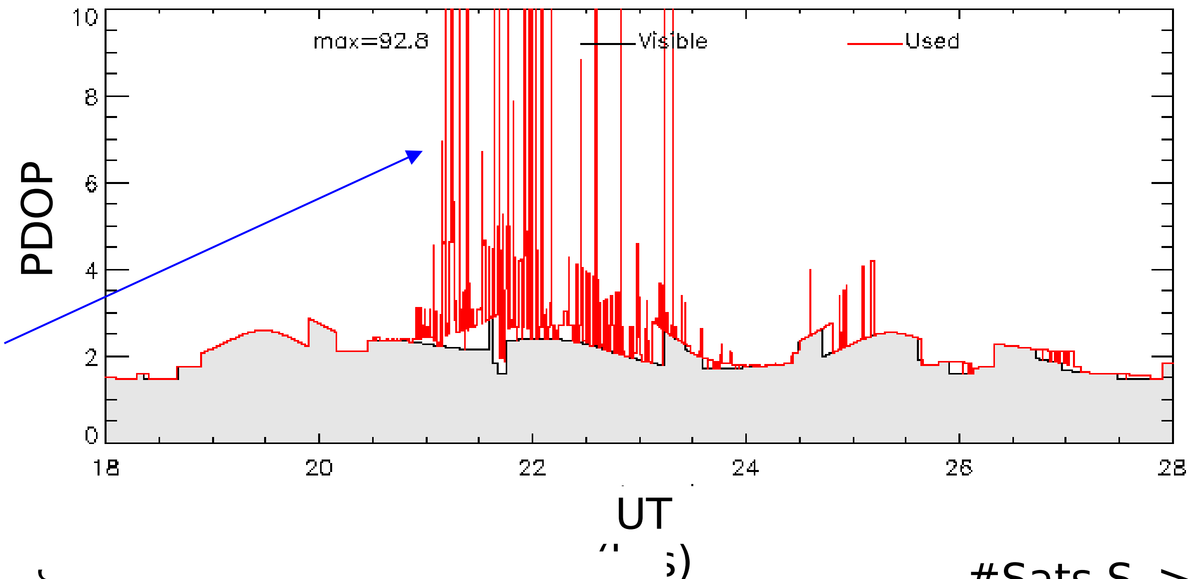
Position errors grow as
number of available satellites is reduced



Geometrical Errors and Ranging Errors

Theoretical and measured Dilution of Precision (DOP)

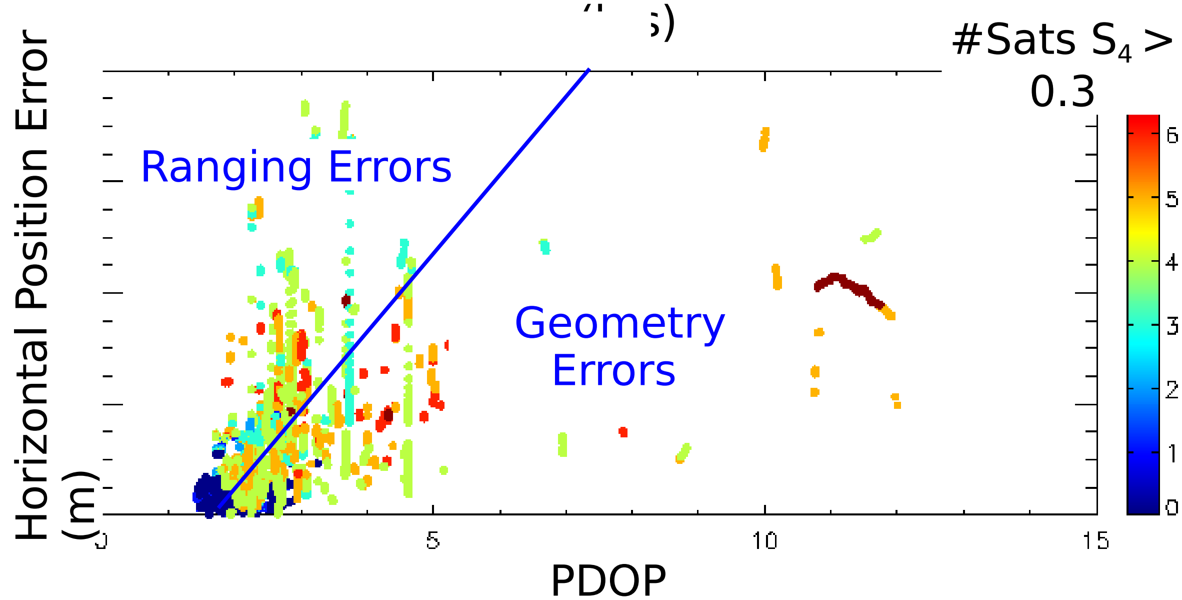
Spikes occur when a satellite becomes temporarily unavailable (timescale ~ seconds, dictated by satellite and plasma velocities)



Large DOP generally leads to large errors, but ...

position error can be large even when DOP is good (>70 m with PDOP of 3)!

Conclusion: scintillation causes *ranging errors*



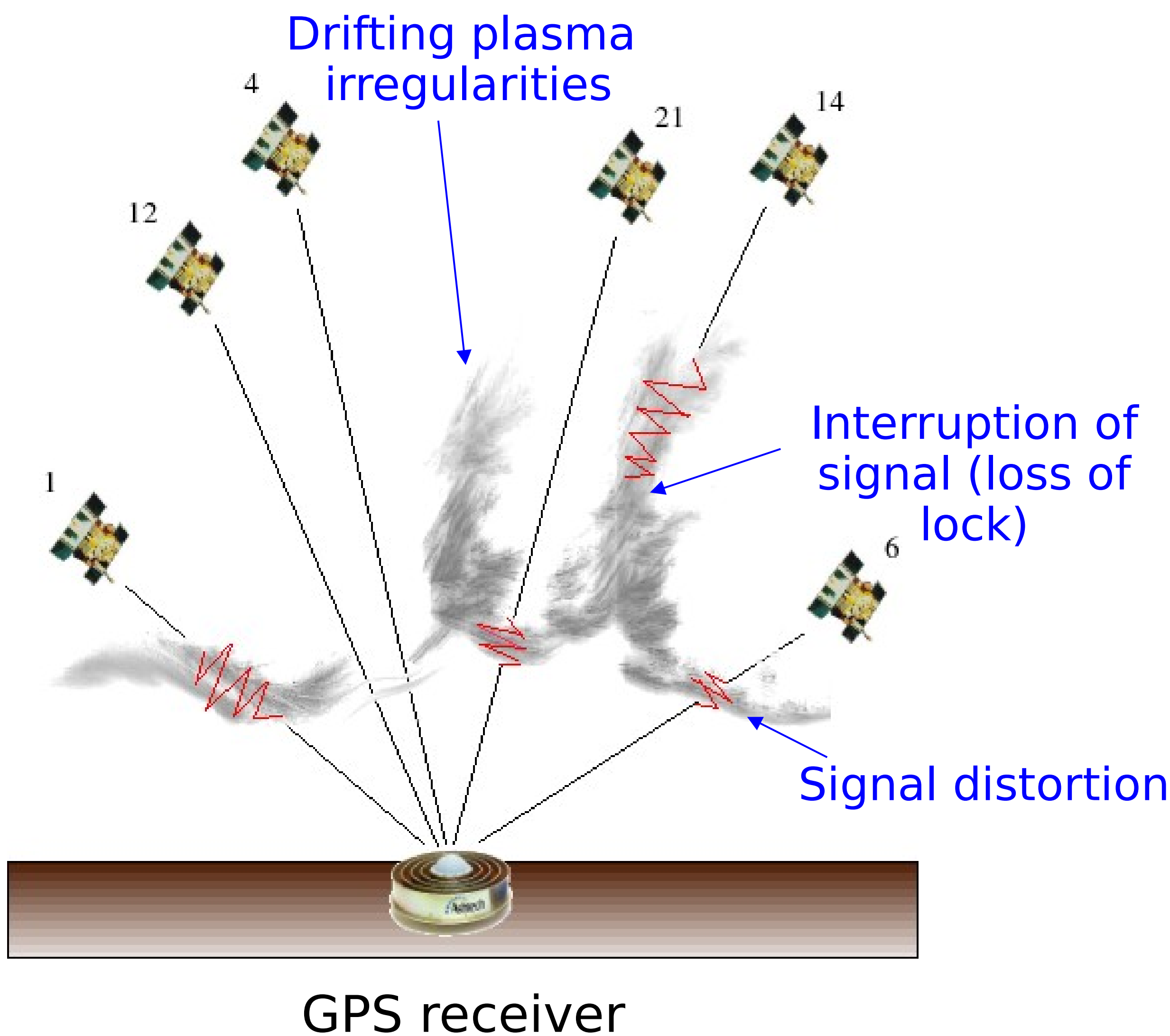
Modeling the Effects of Scintillation on GPS

Two principal effects to model:

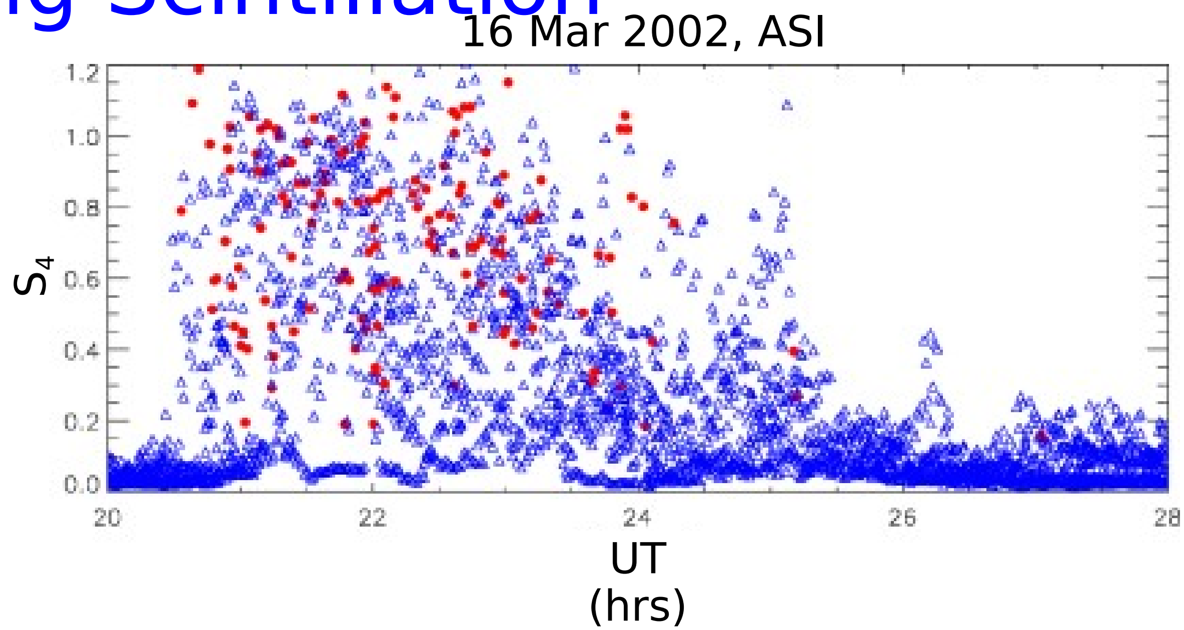
- Intermittent availability
- Induced ranging errors

For realistic predictions, model must couple these effects with the constellation geometry

e.g. distortion of signal from a lone zenith satellite much more damaging than from a redundant mid-elevation satellite



Modeling GPS Satellite Availability During Scintillation

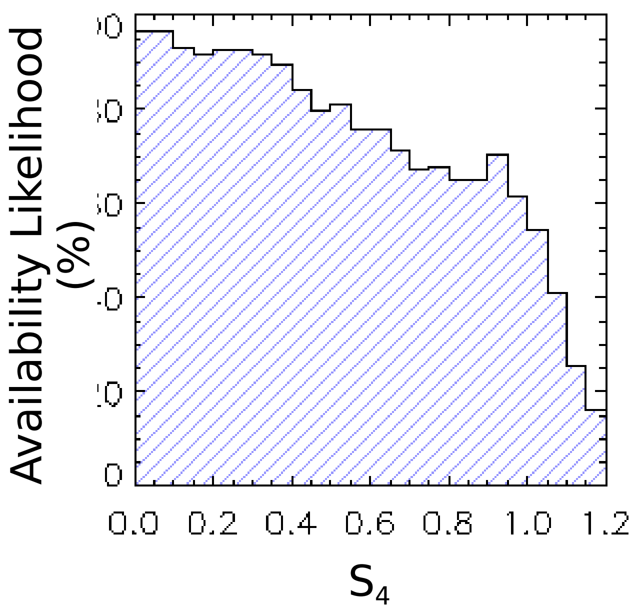


Quality receivers report which satellites used in NAV

Example:

blue = used in NAV

red = not available (corresponds to spike in DOP)



Likelihood satellite will be available decreases as scintillation intensity increases. Each receiver type
will have its own distribution.

Best metric might depend on receiver's “failure mode”

- If fades tend to break delay lock loop (DLL), use S_4.
- If due to phase fluctuations tend to break the phase lock loop (PLL), use σ_φ.

Simulating GPS Position Errors

Once we have modeled which satellites the receiver will track, we model the ranging errors and perform a standard navigation solution for the perturbed receiver position.

GPS range equation for each satellite, *k*:

$$P_{rs}^k + C_r + E_{rs}^k = \|\boldsymbol{R}_r - \boldsymbol{R}_s^k\|, \quad k = 1, \ldots, n$$

We model the k^{th} pseudorange:

$$\underbrace{P_{rs}^k}_{\textit{modeled pseudorange}} = \underbrace{\|\boldsymbol{R}_r^0 - \boldsymbol{R}_s^k\|}_{\textit{true range (via ephemeris)}} + \underbrace{[\gamma_s \hat{\phi}] S_4^k}_{\textit{scintillation induced ranging error}}$$

Linearize the range equations about an initial estimate and solve by iteration:

$$\underbrace{\begin{bmatrix} (X_r - X_s^1)/R_{rs}^1 & (Y_r - Y_s^1)/R_{rs}^1 & (Z_r - Z_s^1)/R_{rs}^1 & (-1) \\ (X_r - X_s^2)/R_{rs}^2 & (Y_r - Y_s^2)/R_{rs}^2 & (Z_r - Z_s^2)/R_{rs}^2 & (-1) \\ \vdots & \vdots & \vdots & (-1) \\ (X_r - X_s^n)/R_{rs}^n & (Y_r - Y_s^n)/R_{rs}^n & (Z_r - Z_s^n)/R_{rs}^n & (-1) \end{bmatrix}}_{\boldsymbol{A}} \underbrace{\begin{bmatrix} dx \\ dy \\ dz \\ dc \end{bmatrix}}_{\boldsymbol{D}} = \underbrace{\begin{bmatrix} P_{rs}^1 - R_{rs}^1 \\ P_{rs}^2 - R_{rs}^2 \\ \vdots \\ P_{rs}^n - R_{rs}^n \end{bmatrix}}_{\boldsymbol{L}}$$

where

$$R_{rs}^k = \|\boldsymbol{R}_r - \boldsymbol{R}_s^k\|$$

Least squares solution to the over-determined system $\boldsymbol{A}\boldsymbol{D} = \boldsymbol{L}$ is $\boldsymbol{D} = (\boldsymbol{A}^T \boldsymbol{A})^{-1} \boldsymbol{A}^T \boldsymbol{L}$

Update the receiver position $\boldsymbol{R}_r \to \boldsymbol{R}_r + [D[1], D[2], D[3]]^T$ and repeat until convergence.

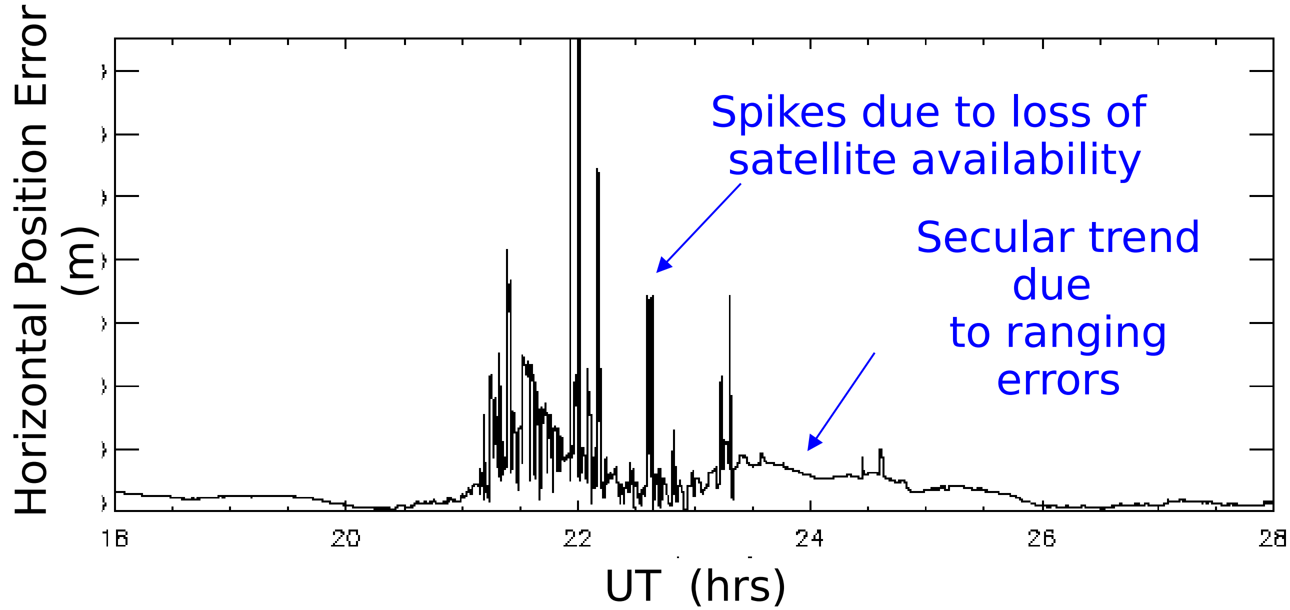
Application of the Model: Positioning Errors at Ascension Island

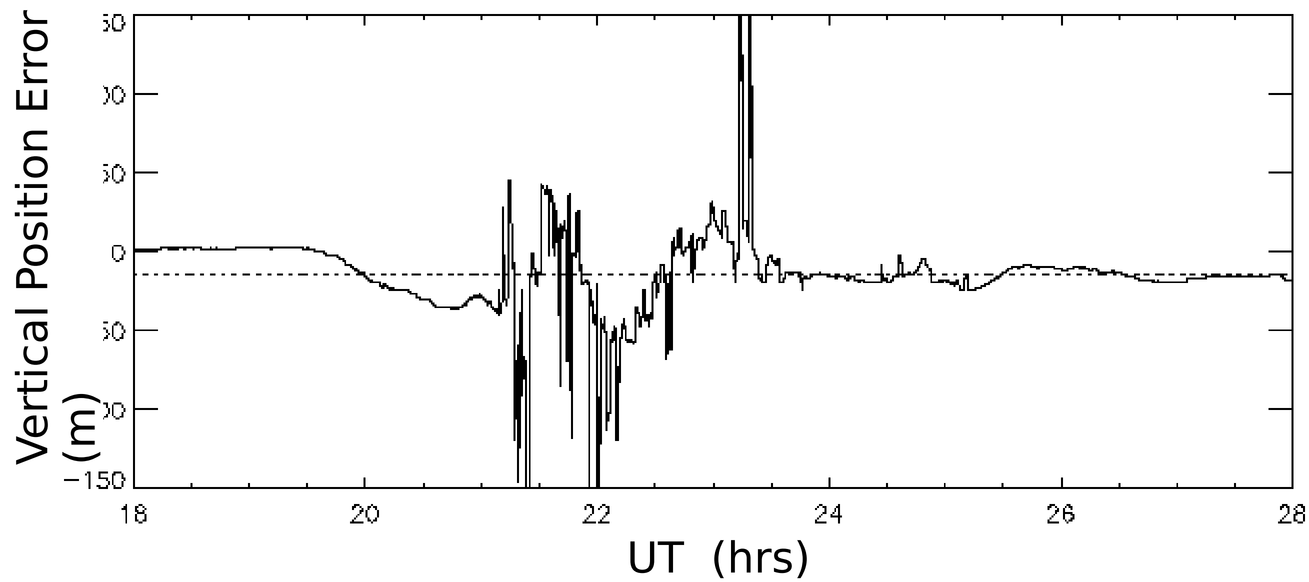
Actual positioning errors
at ASI on 16 mar 2002

Goal:

Using only measurements of S_4 and precise ephemeris, reproduce these position error results.

Only scintillation errors are included, assumes other effects negligible by comparison, including satellite and receiver clock errors, tropospheric errors, etc.





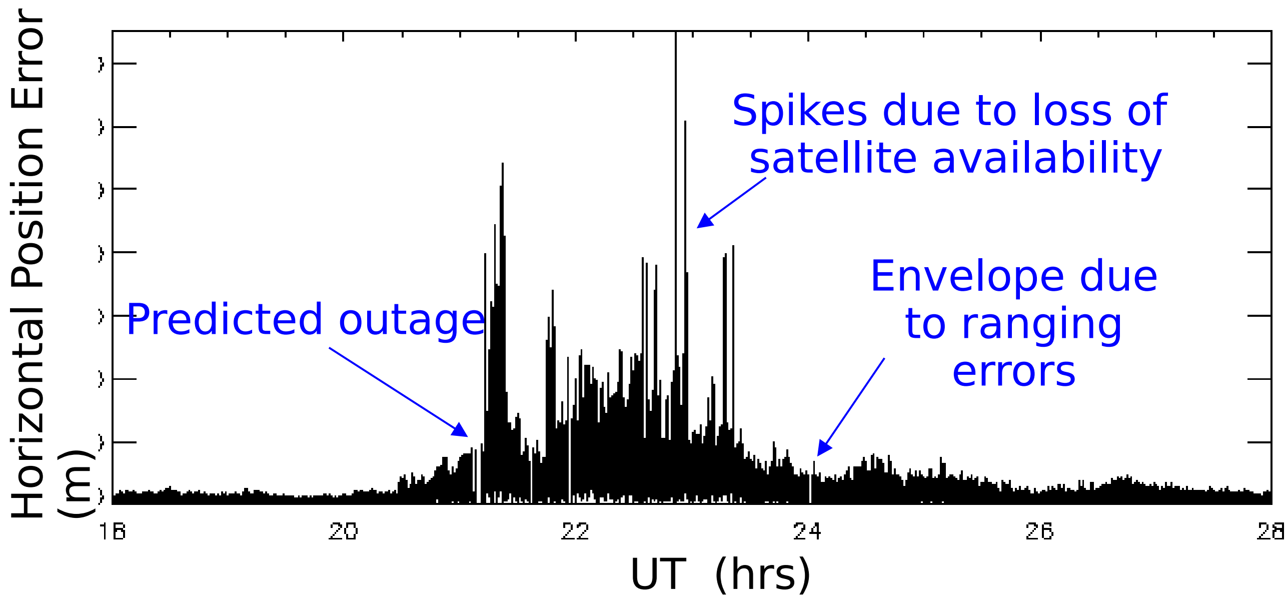
Preliminary Simulation Results

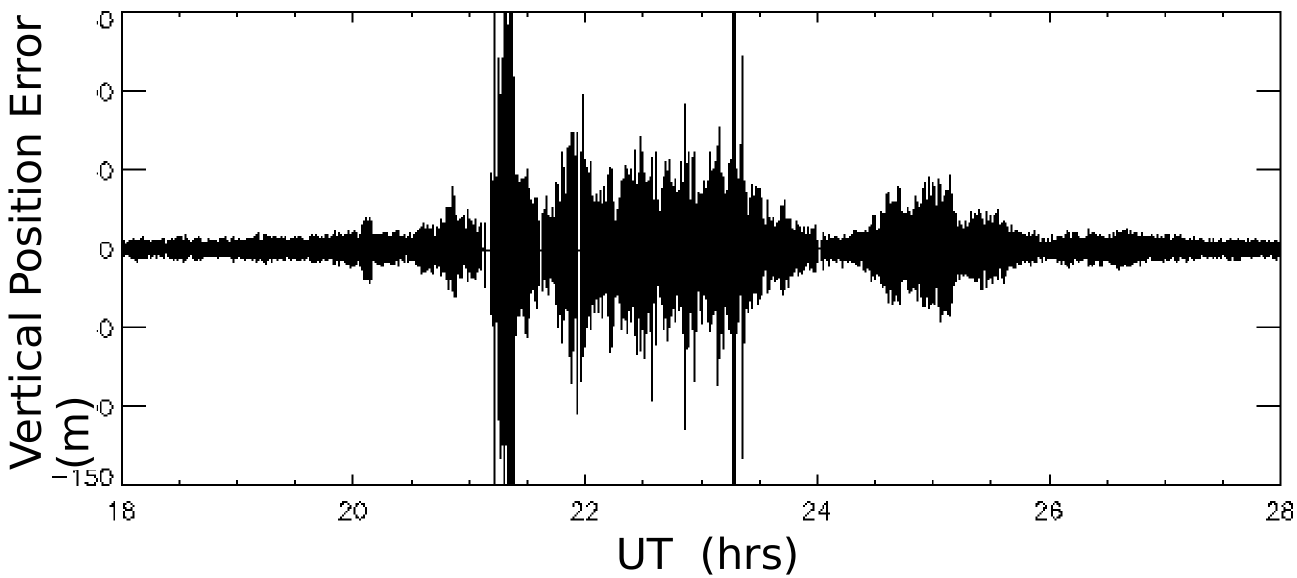
Simulation results using the scaling factor, γ_s = 70 m

Explanation for rapid fluctuations:

Random range perturbations are not correlated in time, unlike in the real world

Even though we have an S_4 measurement only once per minute, we evaluate the model every second so we can do statistics.



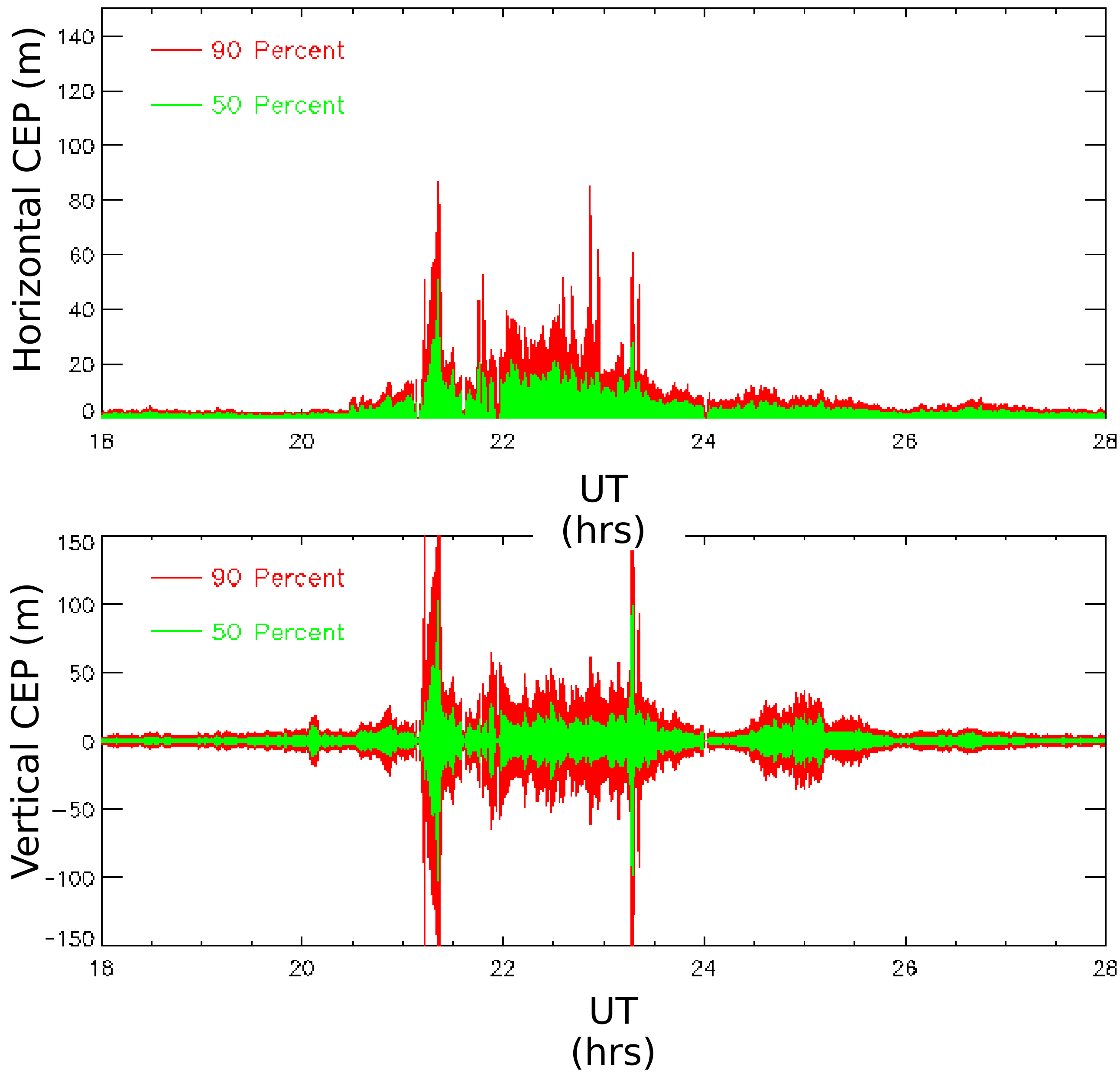


Statistical Analysis of the Simulation Results

Sixty realizations per minute allow us to estimate CEP

We can also invert these statistics: e.g., for a given accuracy requirement, report the probability that this requirement is met

Coupled with a regional model of scintillation intensity (e.g., IONSCINT-G, model can generate regional position error maps



Conclusions

- Ionospheric scintillation contributes to GPS positioning errors in two ways:
  - Intermittent link loss which degrades the effective constellation geometry
  - Ranging errors along each scintillating satellite-receiver link
- Model presented here couples both effects to statistically mimic scintillation induced errors
  - Simple parameters tunable for different receiver types
  - More sophisticated representations under investigation
- The model can predict (statistically) receiver outages and time-series of positioning errors from a single receiver; coupled with regional scintillation specification (i.e., SCINDA, IONSCINT) it can generate regional GPS error maps
- AFRL possesses extensive solar maximum data set of GPS performance during scintillation supporting unique capability for algorithm development

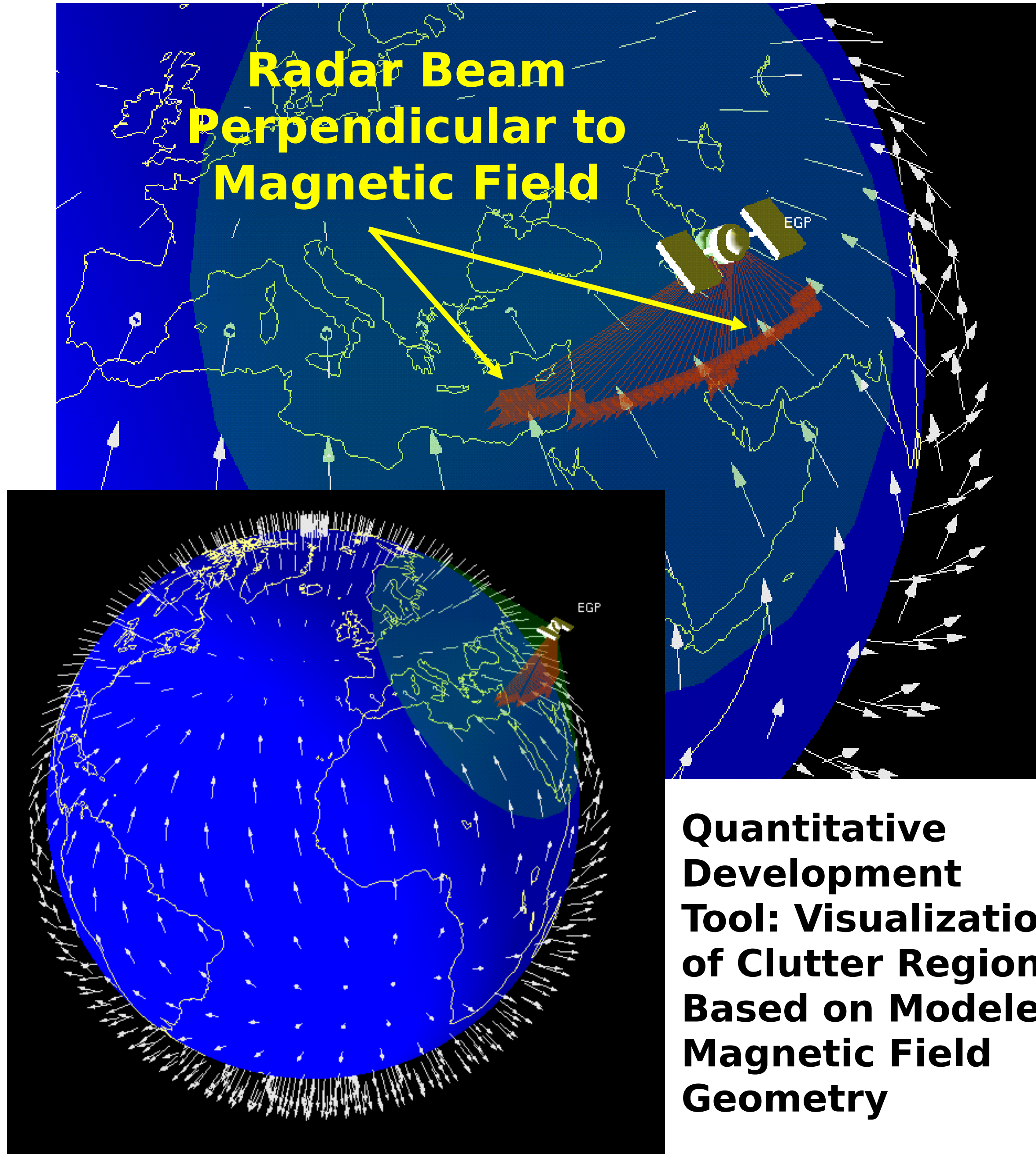
Future Tasks
Space Environment M&S

- Reasonable fidelity GPS navigation error tool
  - Impact still TBD; probably most significant unresolved space weather issue; requires simulation to address
  - Leverages on-going SMC and ICR&D project and FY04 investment
  - Questions should be answered well before next solar maximum (2010-2012)

- Include ‘frequency selective’ scintillation phenomena for wide band waveforms
  - Leverages current joint US-UK data collection project and past Space-based radar (SBR) simulation investments
  - Expands utility to ground and space-based radar surveillance communities
  - Include scintillation in existing SBR simulation (finite task)

onospheric Effects on SBR Analysis & Simulation Tool

- SBR system susceptible to distributed clutter at high & low latitudes
  - Incorporating high latitude clutter model
  - Equatorial model in development
- Scintillation, TEC effects to be added
- Includes radar operation parameters and signal processing
- Maps response to frequency domain



Quantitative Development Tool: Visualization of Clutter Regions Based on Modeled Magnetic Field Geometry